DEVELOPING A DESIGN METHODOLOGY FOR REINFORCING CRACK-LIKE DEFECTS IN THE LONGITUDINAL ELECTRONIC RESISTANCE WELDED SEAMS OF TRANSMISSION PIPELINES

A Thesis

by

JONATHAN DAVID RICKERT

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Anastasia H. Muliana
Committee Members,	Alan Freed
	Harry Hogan
Head of Department,	Andreas Polycarpou

December 2018

Major Subject: Mechanical Engineering

ABSTRACT

Vintage oil and gas transmission pipelines manufactured between 1920 and 1970 were typically constructed using a welding process known as electronic resistance welding, or ERW. At the time, this welding process was susceptible to multiple quality control problems which created small inclusions and flaws at the longitudinal weld seam at the time of manufacture. When the pipes were placed in service, cyclic pressure cycles and environmental corrosion would weaken these flaws, forming crack-like defects. The longitudinal weld seam also exhibits brittle behavior due to the heat affected zone formed by the welding process. As a result, the crack-like defects that form at or near the weld seam grow from cyclic fatigue until they reach a critical size and rupture.

It has been shown that carbon-epoxy reinforcements are economical and effective reinforcements for improving the cyclic fatigue performance as well as restoring the burst pressure near the flaw. The following thesis explores the state of the art research related to carbon-epoxy reinforcements and fracture mechanics, and then recommends a design methodology that could be adapted by pipeline operators and regulators to address this special threat to pipeline integrity. Future work in modeling the crack growth of reinforced flaws is discussed.

DEDICATION

I dedicate this thesis to my wife who has lovingly and graciously supported me throughout my studies.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Muliana, and my committee members, Dr. Freed, and Dr. Hogan for their guidance and support throughout the course of this research.

A special thanks to Dr. Chris Alexander for his support and mentorship. Thanks also go to my friends and colleagues as well as the department of mechanical engineering staff, faculty, and advisors.

Finally, thanks to my family for their encouragement and to my wife for her patience and love.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of the advisor, Professor Muliana and committee members, Professor Freed and Professor Hogan of the department of Mechanical Engineering. All work for the thesis was completed independently by the student.

Funding Sources

There are no outside funding contributions to acknowledge related to the research and compilation of this document.

NOMENCLATURE

ERW	Electronic Resistance Welding
COV	Coefficient of Variation
SMYS	Specified Minimum Yield Strength
MOP	Maximum Operating Pressure
Line Pipe	Industry term for any pipe used to transport petrochemicals
Bondline	The longitudinal weld seam in an ERW pipe
In-line Inspection Tools	Tools that travel inside pipelines to collect data
Fracture Toughness	A material property that characterizes ductility
Base Pipe	The main pipe material, not associated with the weld seam
Burst Pressure	The pressure at which a pipe will burst
Pipeline Operator	Any entity or organization that owns and operates a pipeline
FEA	Finite Element Analysis
Stress Corrosion Cracking	Crack formation in a corrosive environment
Toughness Controlled Failures	Pipes fail due to brittle fracture
Flow Stress Controlled Failures	Pipes fail due to ductile behavior

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CHAPTER I

INTRODUCTION

It can be shown that carbon-epoxy reinforcements improve both the ultimate burst pressure and fatigue performance of a section of ERW pipe containing a longitudinal crack like defect. Carbon-Epoxy systems are useful for repairing cracks because of their high stiffness compared to other composites. Currently, no systematic design methodology serves to guide pipeline operators in repairing these cracks [2]. The subsequent chapters serve to summarize a recommended design procedure based on the current fracture mechanics models and the needs of the pipeline operators. A design methodology should consider the fracture toughness, operating pressure, and crack geometry to determine the appropriate reinforcement thickness, see Figure 1.

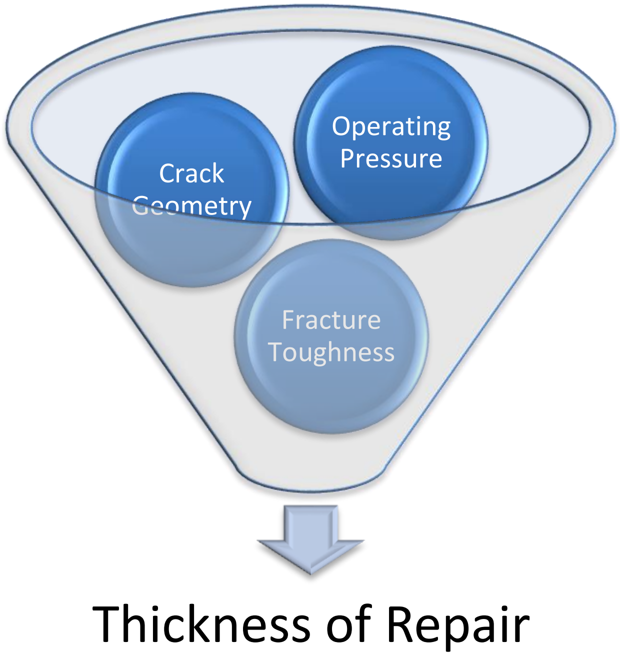


Figure 1 – Inputs that influence the design of a composite repair

CHAPTER II

STATE OF THE ART REVIEW

Background

Beginning in the 1920's, a line pipe manufacturing process known as Electronic Resistance Welding (ERW) was introduced to the petrochemical transportation industry. From 1920 till around 1970, pipes manufactured using this welding technique were susceptible to many quality control problems at the weld seam, or bondline that runs longitudinally down the shaft of the pipe [1]. Welds were often incomplete or flawed due to poor contact resistance in the electrical heating elements causing inadequate metal fusion, which is critical to the welding process [1]. Newly manufactured pipes passed an initial hydrostatic pressure inspection at the manufacturing facility even though they contained small flaws near the bondline [1]. Over time, cyclic pressure cycles from in service ERW pipelines caused these defects to grow to a critical size, inducing ruptures and leaks.

The manufacturing process of ERW pipes involves rolling a flat plate of steel called a "skelp" into a cylindrical form [1]. The cylindrical form contains a seam that is then joined by means of electrical resistance heating and mechanical pressure. Excess material is removed from the bondline with a cutting tool and then the seam undergoes a heat treatment process. The pipe is rolled, welded, and heat treated as a continuous process. For clarity, **Figure 2** shows a top down view of the ERW manufacturing process.

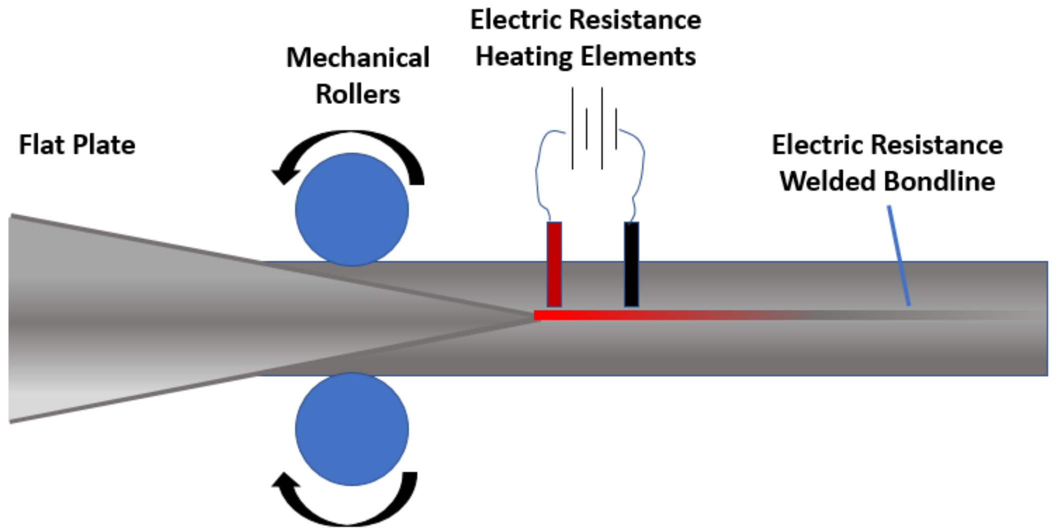


Figure 2 - ERW pipeline manufacturing

Sections of pipe are sized and cut before a hydrostatic pressure test is performed to check for flaws in the welding process. The pipe manufacturing company only performed these pressure tests just slightly beyond their maximum operating pressure (MOP) of 72% SMYS. Prior to 1960 the hydrostatic pressure test was only performed to 75% SMYS, and in the 1970’s the test was performed at 80% SMYS. By today’s standards, the adequate pressure test for these pipes should have been 90% SMYS. Therefore, pipes manufactured prior to 1970 contained small flaws that went undetected during quality testing [1].

After many years in service, cyclic pressure cycles and environmental corrosion may cause the undetected flaws within the pipes to propagate into crack-like defects [1]. Pipeline operators can use in-line inspection tools to identify the location and size of cracks that have reached a certain dimension. Once a defect has been identified, pipeline engineers determine whether it is a threat to pipeline integrity. **Figure 3** shows several common crack-like defects that can form on or near the ERW bondline in pipes manufactured between 1920 and 1970 [3] [1].

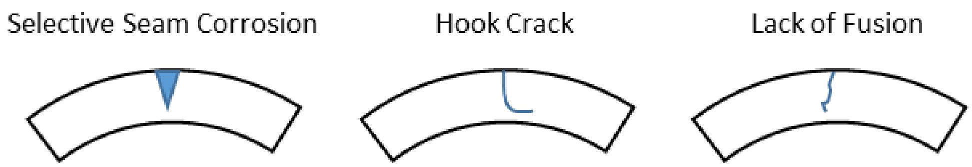


Figure 3 - Common crack-like defects in ERW seams

Vintage pipelines are susceptible to multiple forms of cracking near the weld seam, where the pipe also exhibits brittle behavior due to the heat affected zone created after the welding process. Therefore, the fracture toughness at or near the bondline is extremely low compared to the base pipe, which leaves the pipe vulnerable to leaking or rupturing due to a defect [1]. Crack-like defects may form in three distinct regions: in the base pipe, near the bondline, and on the bondline. **Figure 4** illustrates an example of how toughness varies with proximity to the ERW bond-line [4]. ERW pipelines create a “perfect storm” in that they were widely used, had a predisposition to small flaws in the bondline, and their brittle mechanical behavior. As such, cracks may go undetected until the pipeline catastrophically fails in a sudden rupture or leak.

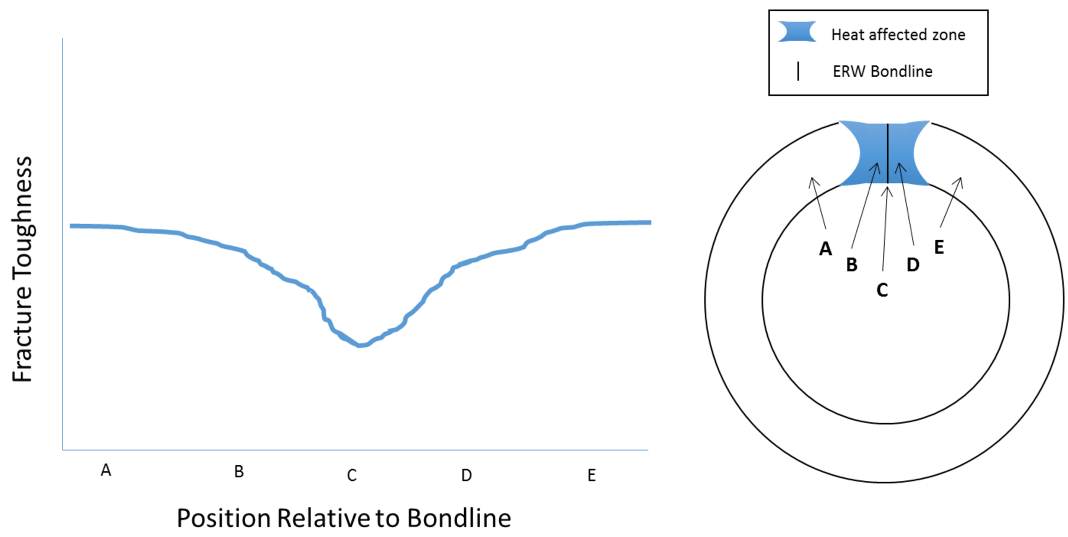


Figure 4 - Fracture toughness behavior or ERW seams

Assessing the Threat - Modeling Fractures

Pipeline engineers must be able to assess the geometry of the flaw as well as consider the fracture toughness at the location of the flaw itself, as flaws occurring at or near the bondline are particularly dangerous. An appropriate fracture mechanics model is required to predict the ultimate failure or burst pressure of a pipe containing crack-like defects.

Fracture mechanics is the main failure mechanism in ERW pipelines with crack-like defects. Many researchers have worked in the field of pipeline fracture mechanics since the 1970's, and the first model for predicting the burst pressure in pipes, known as the Log-Secant method, was developed in 1973. This model is a semi-empirical model that is based on linear elastic fracture mechanics but has correction factors that are set to a range of burst test experiments performed in a well-known study by Battelle's Columbus Laboratories [5]. The Log-Secant method has been the industry standard for the past forty years [6].

While this model has been accepted for many years, it has several drawbacks. One of the main drawbacks is that the Log-Secant model is based on a limited set of experimental burst tests. Thus, it is only reliable within the range of the experimental data the model was developed under. Second, the model is overly conservative for shallow surface defects, requiring pipeline operators to reinforce non-threatening cracks as well as using more composite than necessary, adding to the cost of the repair. Third, the model is not conservative enough when the fracture toughness of the pipe in question is relatively high, leading to inadequate repairs as engineers believe the burst pressure is higher than it really is [6].

In 1996, a pipeline fracture model known as CorLAS was developed and released as a software application [7] [3]. The model was originally developed to predict burst pressures in pipes with stress corrosion cracking, however pipeline engineers have used this model to predict fractures in ERW bondlines [3]. Later on, in 2002, the software was updated to reflect improvements in fracture mechanics modeling [8]. When the updated model was compared to experimental burst data from the well-known Battelle study [5], the model shows extremely high modeling error for low toughness or toughness-controlled fractures [9].

In 2008, the Log-Secant method was modified in an attempt to fix the overly conservative results from the original Log-Secant model [10]. However, the modified Log-Secant model predicts that the burst pressure is independent of the fracture toughness, which is incorrect [6]. Using the modified Log-Secant method results in highly unconservative predictions for low toughness materials [6].

Two new modern fracture mechanics models were published in 2016: the API 579 failure assessment diagram (FAD) model [11] and the PRCI-MAT-8 model [12]. The API FAD model uses modern fracture mechanics principles but includes simplifications that lead to conservative results [3]. The PRCI-MAT-8 accounts for strain hardening and includes more options for approximating the profile of surface flaws [3]. Both the API 579 and PRCI-MAT-8 models incorporate residual forming stresses into the models which can improve the accuracy of predicting toughness-controlled failures [3].

In 2017, Anderson conducted a comprehensive comparison of the well-known fracture mechanics models [9]. The models were compared to burst pressure experiments performed in the Battelle study [5]. It was shown that for the chosen data set, the API 579 and PRCI MAT-8 models performed the best with a coefficient of variation (COV) of 9.9%, an improvement when compared to the original Log-Secant model with a COV of 11.0% [9]. It is important to keep in mind that the Log-Secant model was calibrated to the original data set and thus performs well as long as the flaw and pipe geometry lies within the range of the original burst data [3].

Currently, an effective method for predicting the burst pressure in transmission pipelines with crack-like defects is the use of finite elements analysis (FEA), with the advantage being any crack profile can be modeled accurately [6]. However, FEA requires extensive training and the software is expensive making it impractical to implement industry wide [6]. As a result, pipeline engineers rely on the simplified approach of using fracture mechanics models to assess threats to pipeline integrity.

Experimental Validation of Carbon Epoxy Reinforcements

Meriem-Benziane studied cracks resulting from lack of fusion in pipeline welds. A parametric finite element analysis was performed on the following longitudinal crack geometries;5,10,20,30,40,50,60, and 65 mm. API grade x65 pipe with a radius of 147 mm and a wall thickness of 17.5 mm was utilized in a ¼ pipe model. The length of the ¼ pipe model was 1000 mm. Three internal pressures were modeled for all crack sizes, 65 bar, 70 bar, and 75 bar. The model was a three-dimensional hex dominated mesh with quadratic elements. Mesh refinement was utilized near the crack tip. The mesh consisted of 3250 eight-node brick elements with 35,016 nodes and 105,048 degrees of freedom [13].

Two types of reinforcement were modeled for all crack sizes; a single carbon fiber patch and double carbon fiber patch. The single patch system had a length of 300 mm with a thickness of 12 mm and an adhesive layer of 3mm. The double patch consisted of two carbon fiber layers, each 6mm thick with layers of 1.5 mm adhesive in between. The patch adhesive was an epoxy matrix. The double patch was modeled to be the same thickness as the single patch and utilized two thin layers of carbon fiber. For short cracks less than 10 mm the single patch showed improved performance compared to the double patch. The cracks ranging from 10-20mm were most effectively reinforced using the double patch system. After 20 mm the performance of the two reinforcement systems was nearly identical. For all three pressure levels, the cracks had a factor of safety greater than one when cracks were less than 30mm. Cracks larger than 30 mm were likely to rupture, with safety factors less than one [13].

The study utilized API pipe and modeled the chemical and material properties of actual pipelines. Few papers discuss the reinforcement of pipelines, which is why this paper is significant. FEA results are the most accurate predictions of fracture mechanics results [6], however they are difficult for pipeline operators to use. It takes an experienced analyst and expensive software to produce reliable results. The paper demonstrates the carbon-epoxy reinforcements are effective repairs for restoring the burst strength of pipelines.

A study published in 2016 by Alexander investigates the reinforcement of ERW flaws in 16-in x 0.312-in and 8.625-in x 0.250-in grade X52 pipeline. It was shown that composite reinforcements are feasible methods of reinforcing flaws that interect with ERW weld seams. Two methods of reinforcements were utilized in the study: a hybrid steel sleeve/E-glass, and a carbon-epoxy overwrap. The carbon epoxy system is of interest to this study because it only utilizes composites and does not require the use of steel reinforcement.

Samples were prepared in eight foot sections with welded end caps. Edm notches were introcuded in three evenly sapced locations along the ERW weld seam to ensure that the simulated defects would cause a failure in the unreinforced samples. Simulated defects were canoe shaped and were 0.100 inches deep (32% of the wall thickness). Pressure cycling and burst testing was performed to examine the ultimate strength of the repairs as well as the fatigue life performance [2].

Pressure cycling was performed between 267 and 1,920 psi. For the eight inch unreinforced samples, two failed after just 1 cycle, the remaining three failed after about 150 cycles. The one unreinfroced 16-in sample failed after 350 cycles. Three 8-in samples were reinforced with 0.631 inches of carbon-epoxy wrap. These reinforced samples achieved a target number of 1500 pressure cycles. The 16-in sample were reinforced with 0.701 inches of carbon-epoxy wrap. A target condition of 3,500 pressure cycles was achieved with the 16-in reinforced sample.

In addition, burst tests were performed on separate samples. The six 8-inch unreinforced samples burst at an average of 2,428 psi amd the one unreinforced 16-inch sample burst at 2,304 psi. Three 8-inch samples were reinforced with the carbon-epoxy warp and pressurized to failurel The average burst pressure between the three samples was 9,283 psi which is 382% larger than the unreinforced samples. A 16-inch sample was prepared using the carbon-epoxy reinforcement and was pressurized to failure. The resulting burst pressure was 6,440 psi a 280% increase compared to the unreinforced samples.

In an unpublished study performed by Alexander, several composite reinforcement systems were pressure cycled to determine fatigue performance as a funtion of composite stiffness. One of the best performing reinforcements, was a carbon epoxy overwrap system. The samples in the experiment were 12.75-in, x

0.188-in, grade X52 pipe. Notches were machined on the surface of the samples, extending through 50% of the wall thickness. Various thicknesses of carbon-epoxy wrappings were applied to several samples, and then all samples were cycled to failure with a pressure range of 72% SMYS. Figure 5 shows a correlation between composite thickness and cycles to failure. It appears that increasing the composite stiffness, significantly improves the fatigue performance of a pipe containing a flaw [14].

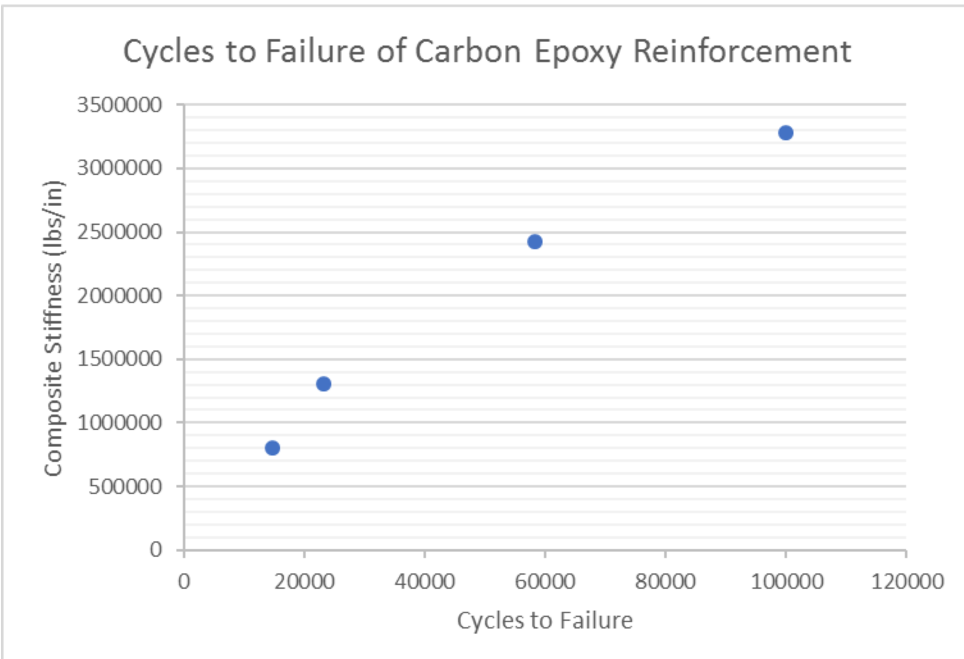


Figure 5 – Experimental Correlation between composite stiffness and cycles to failure [14]

CHAPTER III

METHODOLOGY

Overview

If a crack-like defect is identified as a threat, it is possible to reinforce the crack so that the pipeline may return to normal operating conditions. An economical and effective way to reinforce flaws in pipelines is by utilizing composite material reinforcements. It has been proposed that using carbon-epoxy systems may be effective for repairing crack-like defects in ERW pipelines [1]. Figure 6 is an example of a pipeline that has been reinforced with a carbon-epoxy composite.

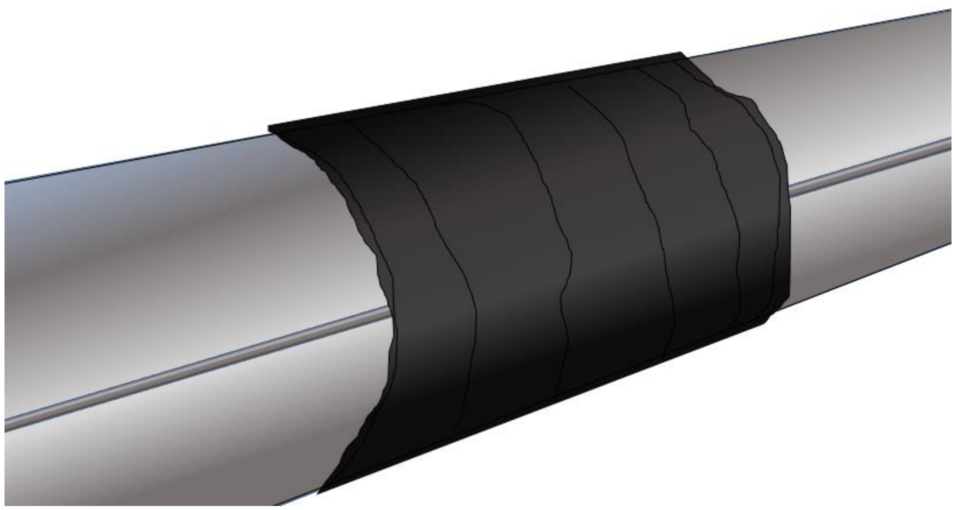


Figure 6 - An example of carbon-epoxy reinforcement system

The goal of the research performed in this thesis is to develop design guidelines for carbon epoxy composite reinforcements of crack-like defects in ERW line pipe. **Figure 7** shows a section of transmission pipeline with a crack-like defect and **Figure 8** shows a composite reinforcement. Note that the key variable is the thickness of the composite since the material properties of carbon epoxy systems are consistent and easily controlled. In order to determine the correct thickness of the repair, one must calculate the remaining strength of the damaged pipe using an appropriate fracture mechanics model as well as verify the fatigue performance of the reinforced flaw.

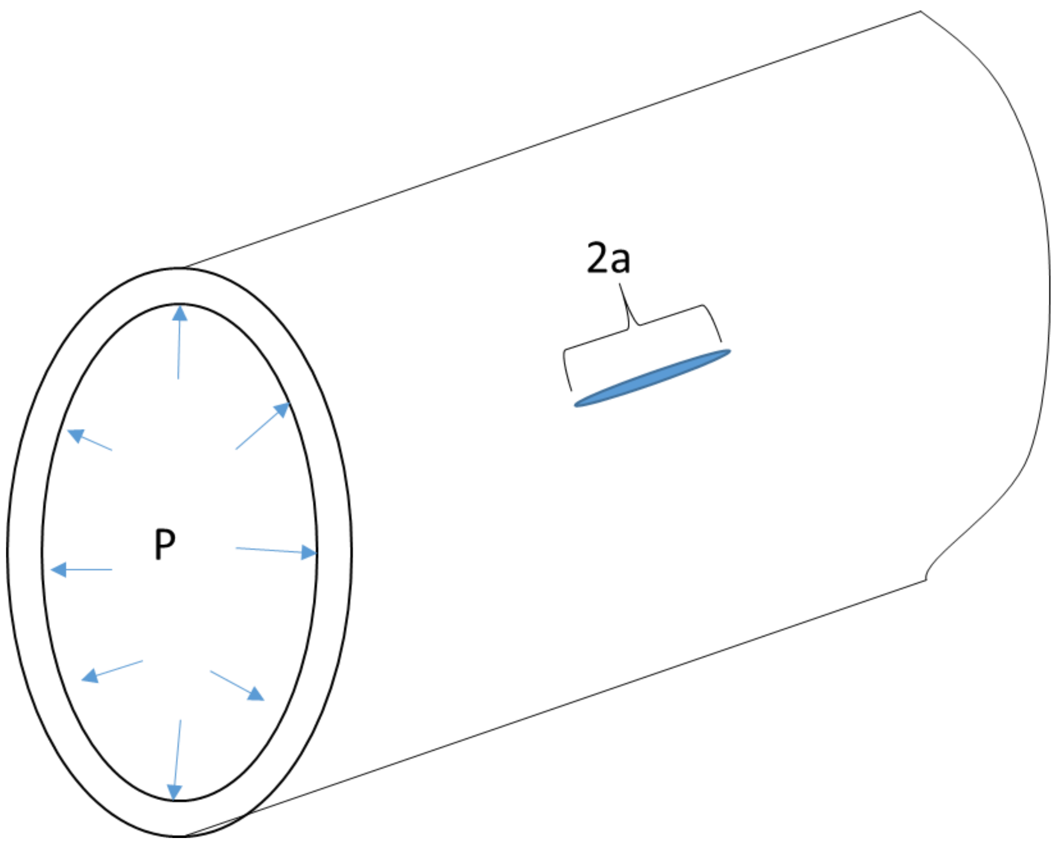


Figure 7 - Transmission Pipeline with Longitudinal Crack

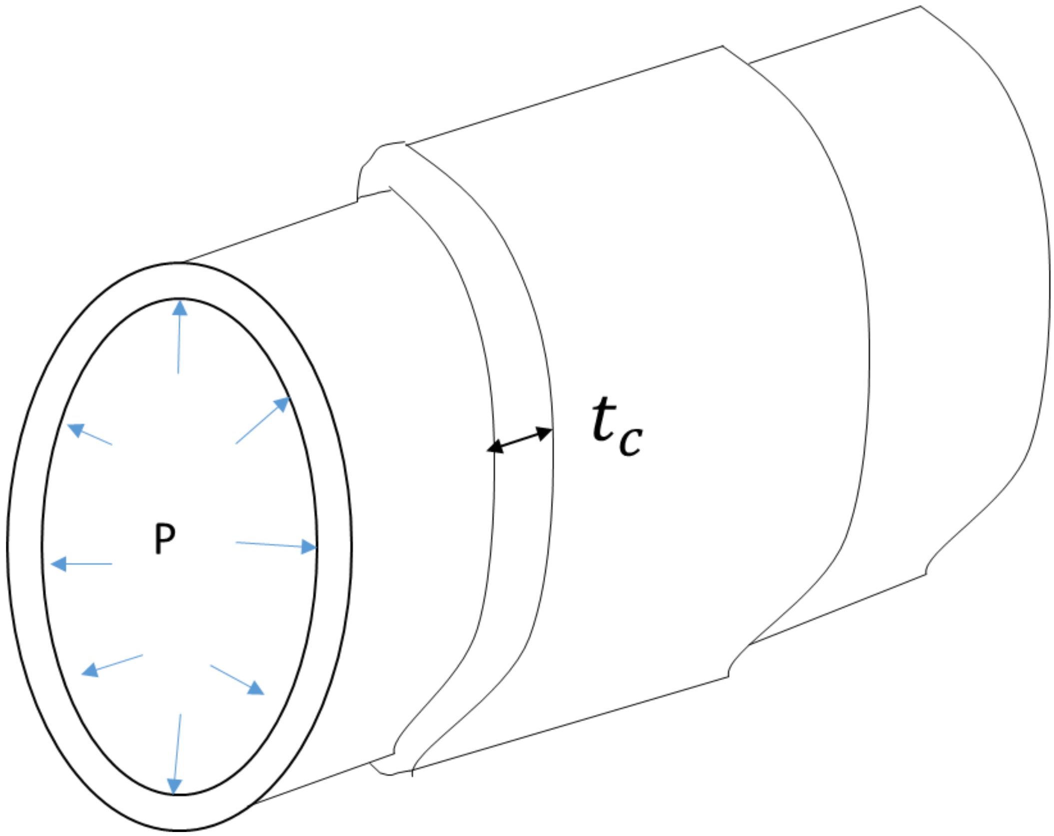


Figure 8 - Transmission pipeline reinforced with composite reinforcement

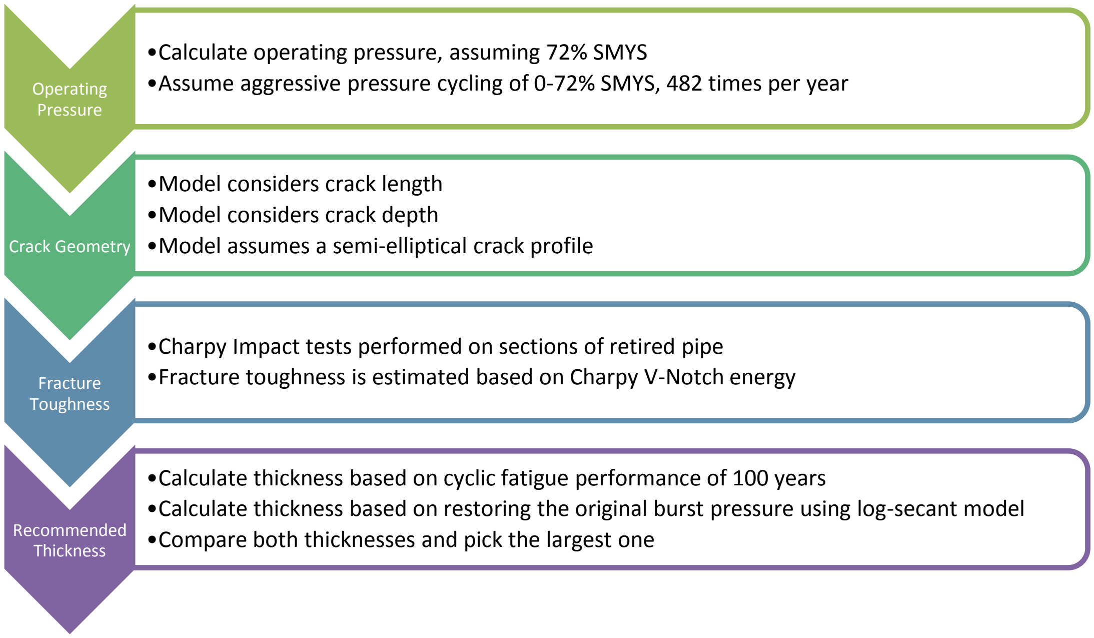


Figure 9 - Design methodology for reinforcing crack-like defects in ERW pipelines

Estimating Fracture Toughness

Performing Charpy Impact Tests is one method of testing the fracture toughness for in service pipelines. A section of pipe is removed and pieces of the pipe are cut, flattened, and machined to conform to ASTM standards. The energy absorbed by the samples is strongly correlated with the fracture toughness of the material [5]. The proposed correlation is given below in equation 1 [5].

$$K_{IC} = \sqrt{\frac{12C_vE}{A_c}} \tag{1}$$

$$K_{IC} = Fracture\ Toughness\ (psi\sqrt{in})$$

$$C_v = Charpy\ Impact\ Energy\ (ft \cdot lbs)$$

$$E = Elastic\ Modulus\ of\ Charpy\ Impact\ Specimen\ (psi)$$

$$A_C = Fracture\ Area\ of\ Charpy\ Impact\ Specimen\ (in^2)$$

$$A_c = wh$$

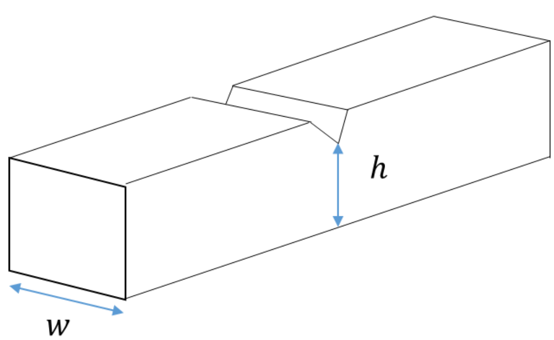


Figure 10 - Calculating fracture area

A study performed in 1973 by Kiefer resulted in a set of semi-empirical equations for predicting the burst pressure of line pipe with longitudinal flaws [5]. The Log-Secant model has been the industry standard for over 40 years [6]. While the model has its limitations, it is well suited for designing composite repairs on low toughness materials because it is likely to yield conservative results.

Modeling Surface Flaw Fractures

$$\frac{K_c^2\pi}{8c_{eq}\bar{\sigma}^2} = \ln\left(sec\left(\frac{\pi M_p \sigma_p}{2\bar{\sigma}}\right)\right) \tag{2}$$

$$\sigma_p = \frac{2\bar{\sigma}}{\pi M_p}\sec^{-1}\left(e^{\frac{K_c^2\pi}{8c_{eq}\bar{\sigma}^2}}\right) \tag{3}$$

$$M_p = \left[\frac{1-\frac{d}{t}}{1-\frac{d}{M_t t}}\right]^{-1} \tag{4}$$

Note that the crack length is modified to reflect the actual area of the surface flaw. If the flaw is assumed to be rectangular, $2c_{eq}$ can be approximated as $2c$.

$$2c_{eq} = \frac{A}{d} \cong \frac{2cd}{d} = 2c \tag{5}$$

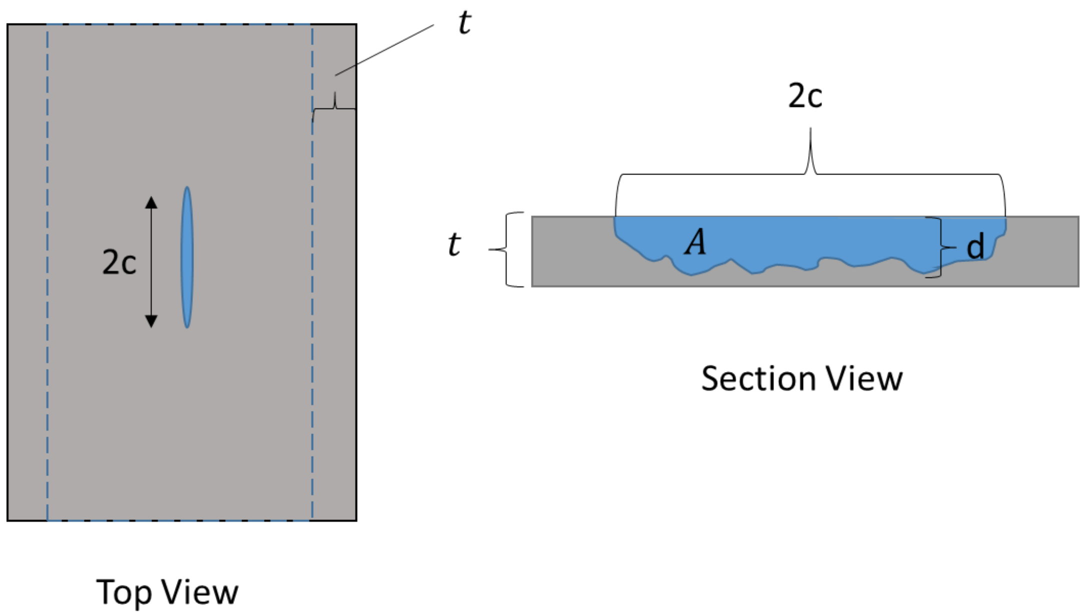


Figure 11 - Modeling surface flaws using Log-Secant method [5]

Estimating Remaining Years of Service

It has been shown that composite stiffness is correlated with improved cycles to failure [2]. Composite stiffness is simply the elastic modulus multiplied by the thickness of the repair. If it is assumed that the elastic modulus for carbon-epoxy systems is about 9,720,000 psi, then it is possible to predict years of service vs. composite thickness. Cycles to failure can be converted to years of service if it assumed that a pipeline is pressure cycled to 72% SMYS 482 times a year. This pressure range and frequency is representative of the most aggressive pipeline operations in the United States.

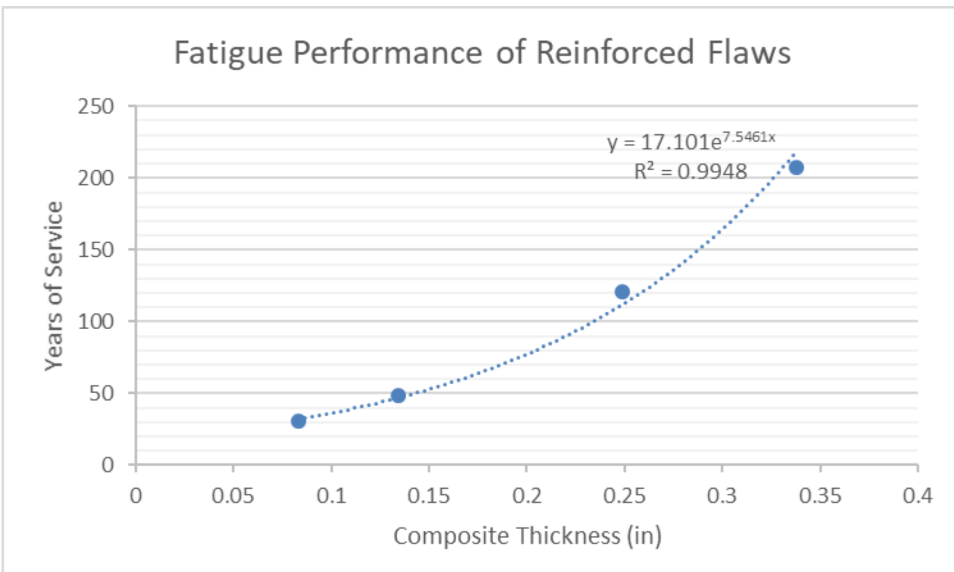


Figure 12 - Estimating remaining years of service based on an experimental correlation

Based on Figure 12, it is recommended that the minimum composite repair for all ERW pipelines to be 0.23 inches thick. This thickness corresponds to a service life of 100 years. The justification for an exponential fit is because crack growth is governed by Paris's Law, which is a first order differential equation, and solutions of first order ODE's are typically exponential curves.

Calculating Composite Thickness

A method of calculating the required repair thickness, involves a shared load between the steel pipe and the composite reinforcement.

$$\sigma_{burst} = Strength\ of\ Composite\ Repair + Strength\ of\ Damaged\ Pipe \quad (6)$$

$$\sigma_{burst} = \frac{2\sigma_c t_c}{OD} + \sigma_p \quad (7)$$

If the pipe is to be repaired such that the ultimate burst pressure of the base pipe is restored. Then equation seven may be rearranged to solve for the thickness of the composite repair.

$$t_c = \frac{(\sigma_{burst} - \sigma_p)OD}{2\sigma_c} \quad (8)$$

$$\sigma_{burst} = burst\ pressure\ of\ the\ reinforced\ pipe\ (psi)$$

$$\sigma_c = Ultimate\ tensile\ strength\ of\ composite\ repair\ (psi)$$

$$t_c = thickness\ of\ composite\ repair\ (in)$$

$$OD = Outer\ diamter\ of\ steel\ pipe\ (in)$$

$$\sigma_p = Predicted\ hoop\ stress\ at\ failure\ for\ steel\ pipe\ (psi)$$

CHAPTER IV

RESULTS

Three grade X52 pipes were chosen as representatives for common ERW line pipe: 8-in, x 0.280-in, 12-in, x 0.188 in, and 24-in, x 0.280-in. Burst pressures were calculated for each unreinforced pipe over a range of Charpy V-Notch energies and crack geometries. The corresponding composite thicknesses are plotted in Figure 13, Figure 14, and Figure 15. The model assumes that enough composite reinforcement will be added such that the pipe is restored to its originally designed burst pressure.

Flaws may occur in the base pipe, near the ERW bondline, or on the ERW bondline, as such, the toughness in these regions was considered for this study. The fracture toughness of the base pipe or parent pipe is typically about 25 ft-lbs for ductile pipeline constructed between 1920 and 1970 [1]. Near the ERW bondline the CVN is about 10 ft-lbs [4] [1] and, if the flaw occurs on or through the bondline the corresponding CVN is about 2 ft-lbs.

8-in Pipeline

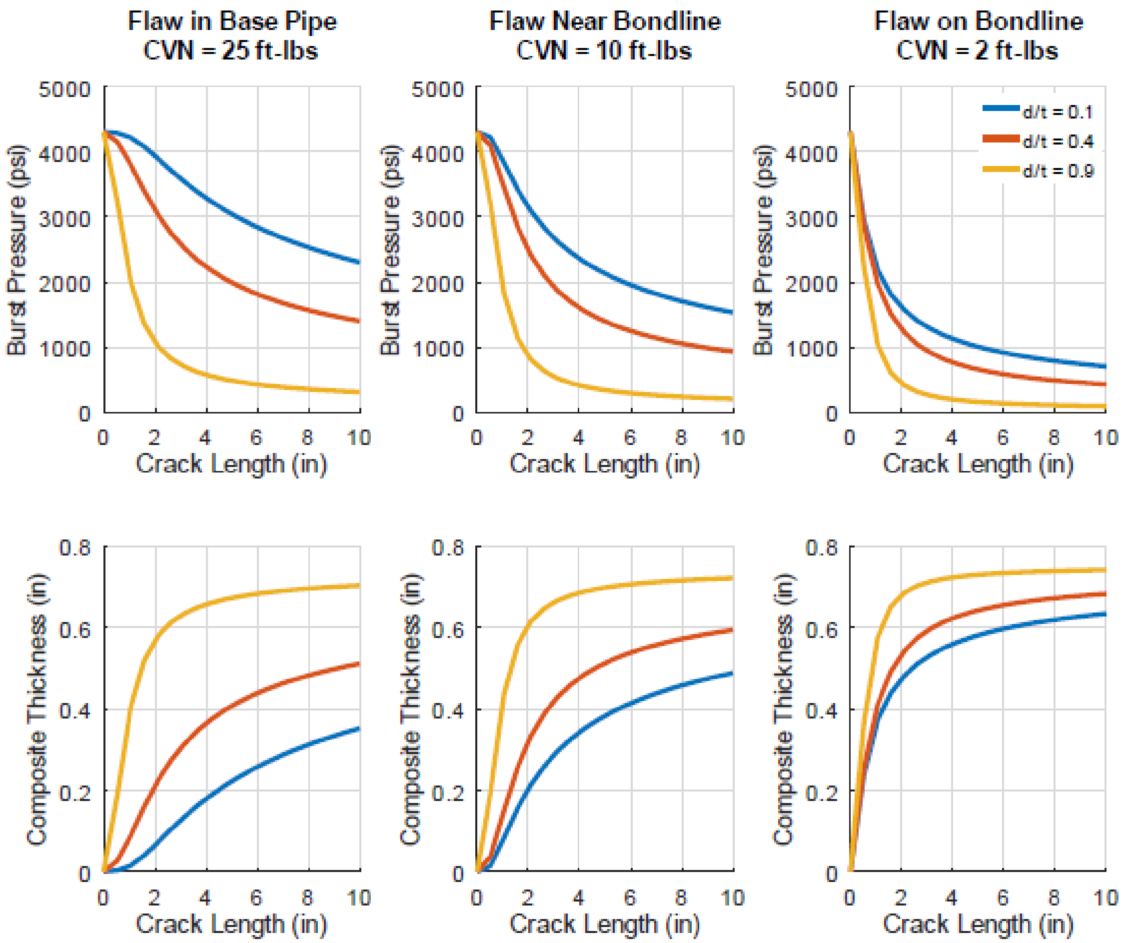


Figure 13 - Reinforcing Flaws in 8-in x 0.280-in, Grade X52 ERW Line Pipe

12-in Pipeline

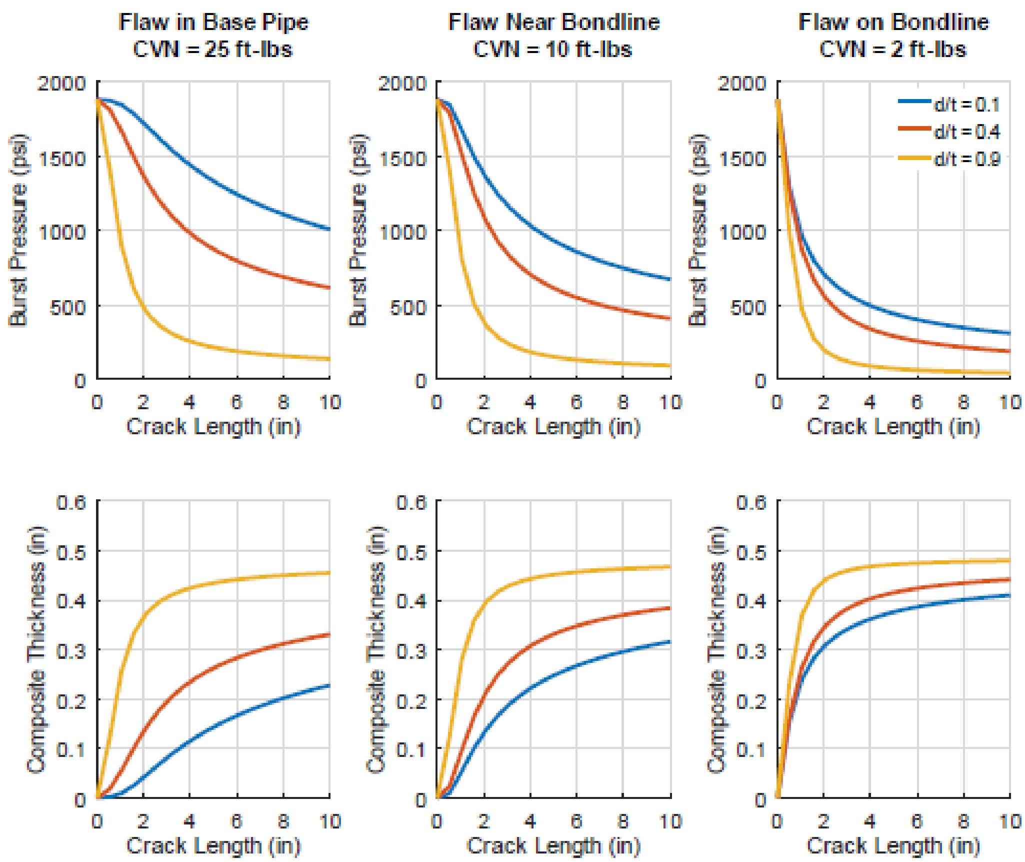


Figure 14 - Reinforcing Flaws in 12-in x 0.188-in, Grade X52 ERW Line Pipe

24-in Pipeline

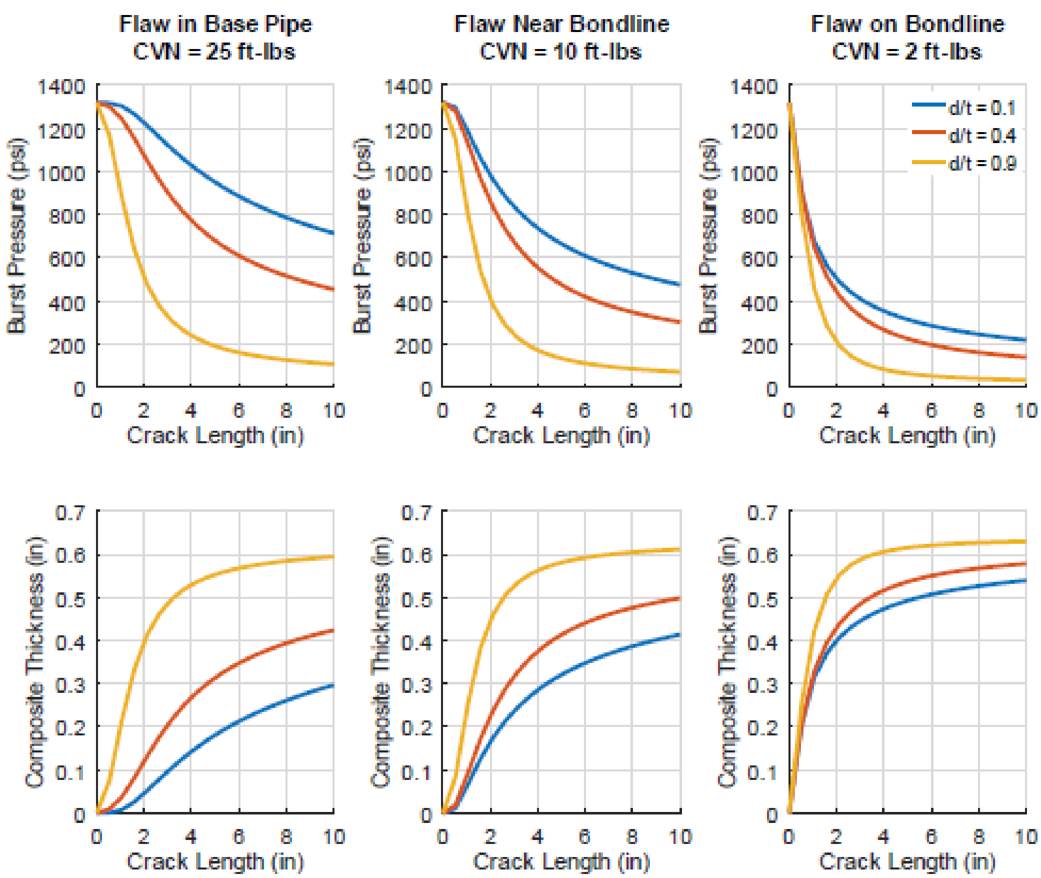


Figure 15 - Reinforcing Flaws in 24-in x 0.25-in, Grade X52 ERW Line Pipe

CHAPTER V

DISCUSSION

Cracks that occur on or near the bondline appear to be very dangerous, with cracks greater than one inch lowering the burst pressure by almost 1000 psi in some cases. As a general trend, deeper surface flaws require more composite reinforcement as expected. It is interesting to note that as the fracture toughness decreases the results become less dependent on flaw depth and more related to flaw length.

LEFM: A poor model for Pipelines

A preliminary approach is to assume that linear elastic fracture mechanics (LEFM) will provide an appropriate model to describe the failure stress of the pipeline. The following equations describe a (LEFM) model for through wall cracks in cylindrical pressure vessels [14].

$$\lambda = \frac{a}{\sqrt{Rt_s}} \tag{9}$$

$$K_I = \sigma\sqrt{\pi a} \cdot F(\lambda) \tag{10}$$

$$F(\lambda) = (1 + 1.25\lambda^2)^{\frac{1}{2}} \quad 0 < \lambda \geq 1 \tag{11}$$

$$F(\lambda) = 0.6 + 0.9\lambda \quad 1 \leq \lambda \leq 5 \tag{12}$$

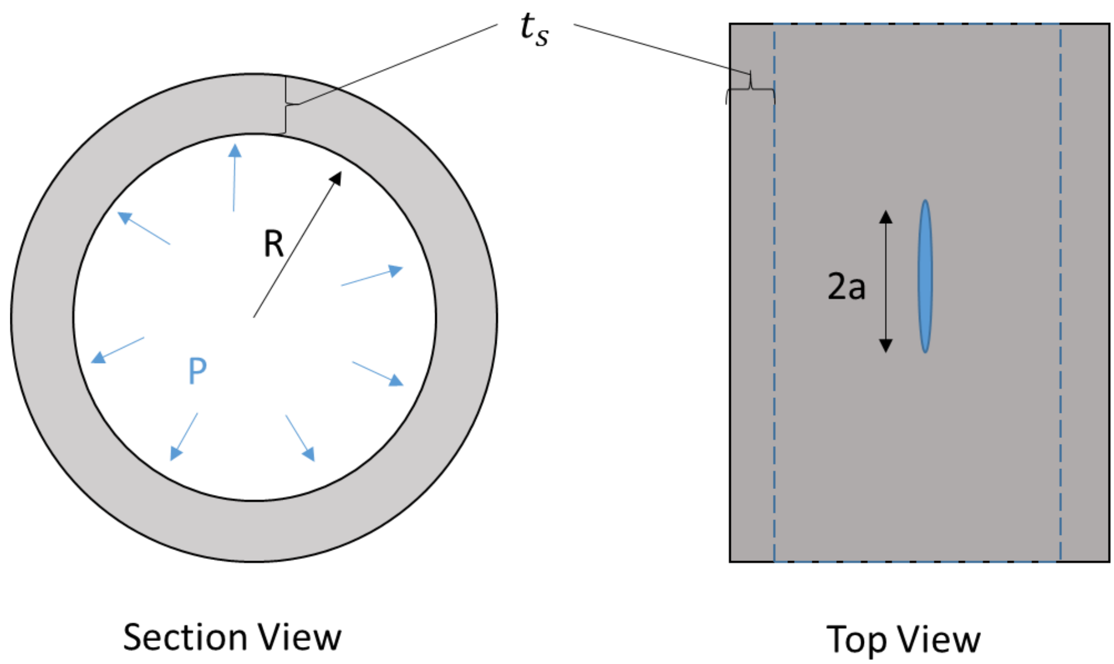


Figure 16 - LEFM Model

Before calculating the effects of the composite reinforcement, it is critical to know the limitations of the LEFM model. Using the correlation between Charpy Impact Energy and Fracture Toughness it is possible to compare the LEFM predictions to experimental results assuming that the impact energy is listed in the data. One such study is the Battelle study conducted in the 1960's [5]. Over 300 fracture initiation experiments were performed on full scale pipeline experiments. Of the 300, experiments 140 experiments were conducted involving longitudinally oriented cracks. Some of the cracks were through wall, while the remaining were surface flaw defects (part way through cracks) [5].

For the purposes of testing the LEFM model, a small selection of the burst experiments were chosen for comparison purposes. All of the pipes were 30 inches in diameter and had similar fracture toughness, tensile strength, and yield strength. The samples were chosen because they all contained longitudinally oriented through wall cracks of various lengths. The selected experimental results are tabulated in Table 1.

Table 1 - Selected results from Battelle study used in comparison. Adapted from[5]

Test No	OD (in)	Wall Thickness (in)	R	Grade	Crack Length (in)	Yield Strength (ksi)	Ultimate Strength (ksi)	CVN 2/3 Size (ft-lbs)	Fracture Toughness (psi√in)	Failure Stress Level (Ksi)
6	30	0.367	14.633	x52	1	58.6	77.3	29	317063	70.6
8	30	0.374	14.626	x52	3.3	60.6	81.3	27	305935	55.8
5	30	0.363	14.637	x52	4.5	58.6	77.3	29	317063	46.8
1	30	0.376	14.624	x52	8.75	61.9	78	30	322484	27.8
30	30	0.328	14.672	x60c	11	67.3	80.8	22	276158	27
26	30	0.328	14.672	x60C	15	68.6	85.2	23	282365	18.3
27	30	0.328	14.672	x60c	20	68.6	85.2	23	282365	14.6

Shown below is a comparison between the predicted failure stress and the actual failure stress. As you can see, the model is very accurate for cracks longer than 10 inches. The model is extremely unconservative and grossly over estimates the failure pressure as the cracks become shorter. There are two reasons for this phenomenon. First, short cracks are likely to have a degree of plastic deformation before rupture, thus invalidating LEFM assumptions. Second, the LEFM model does not consider the yield stress or the ultimate strength of the pipe material to be a limiting factor.

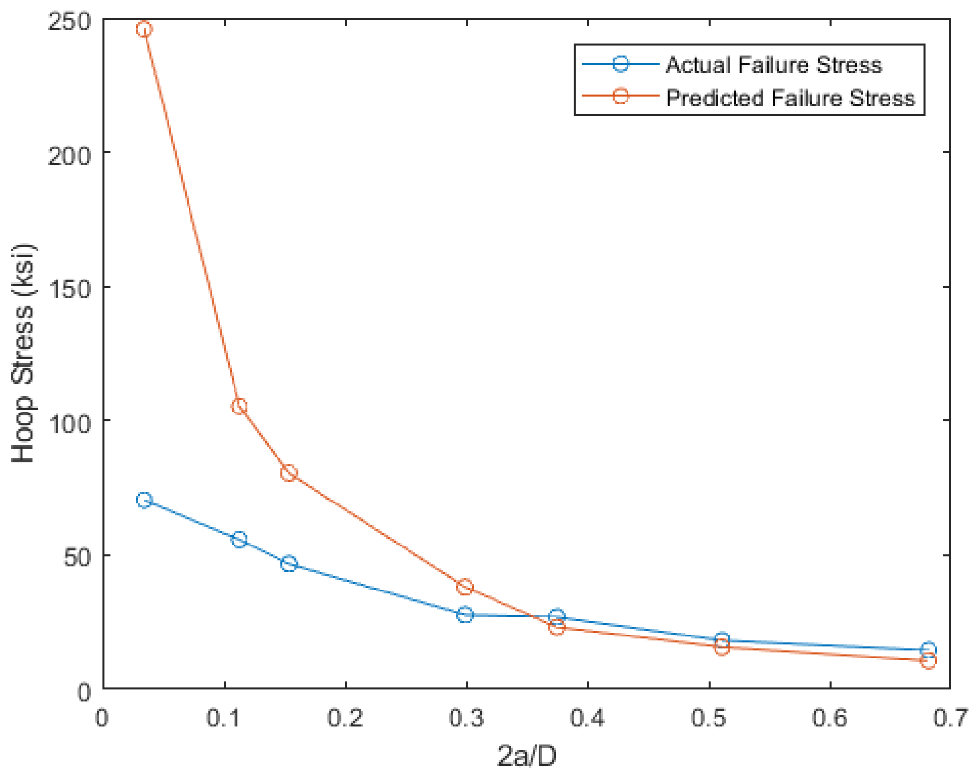


Figure 17 - Comparing LEFM to experimental results

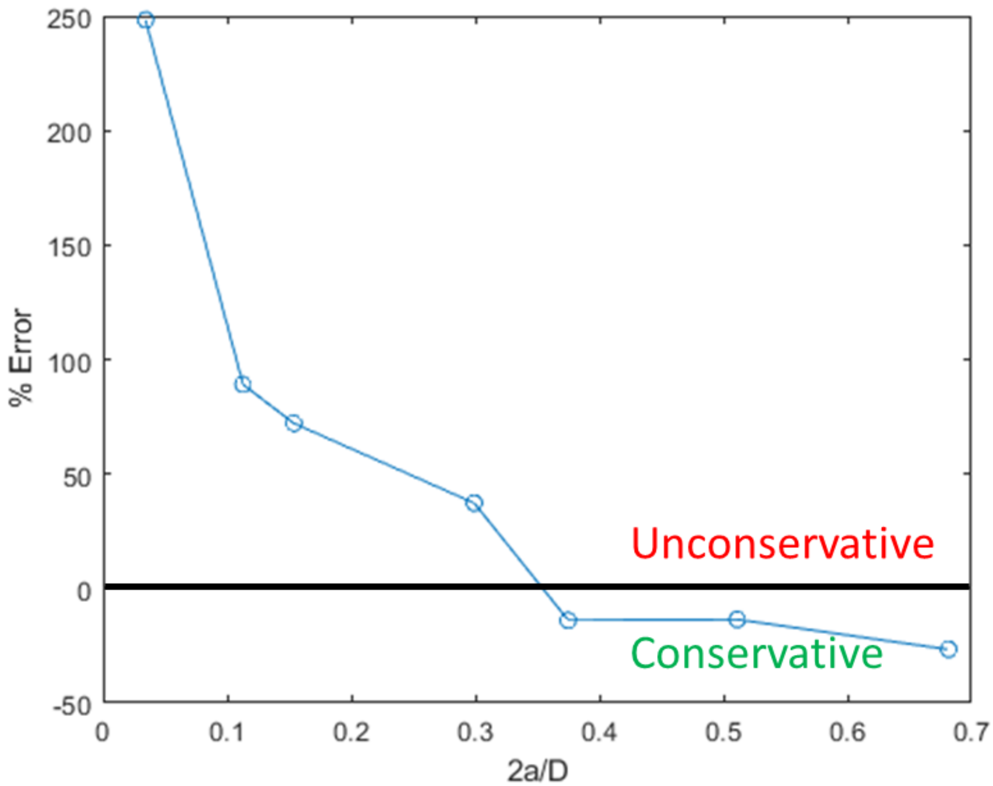


Figure 18 - Percent error of LEFM model

Of course, it is impossible for the pipe to hold pressure past the ultimate strength of the material. A possible solution is to impose an upper ceiling to the LEFM predictions. For shorter cracks, the failure point will lie somewhere between the yield strength and the ultimate strength of the material. Therefore, when the LEFM predictions exceed the yield stress of the material it would be conservative to predict a failure. Shown below are the LEFM predictions with the upper ceiling restriction.

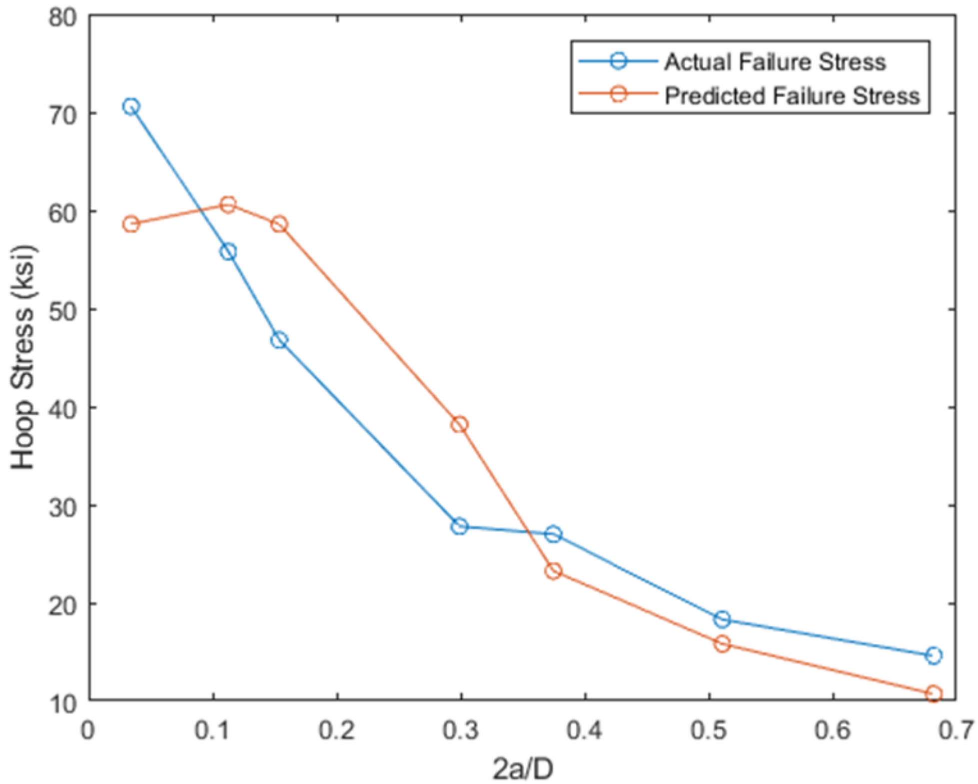


Figure 19 - LEFM with yield stress as upper ceiling

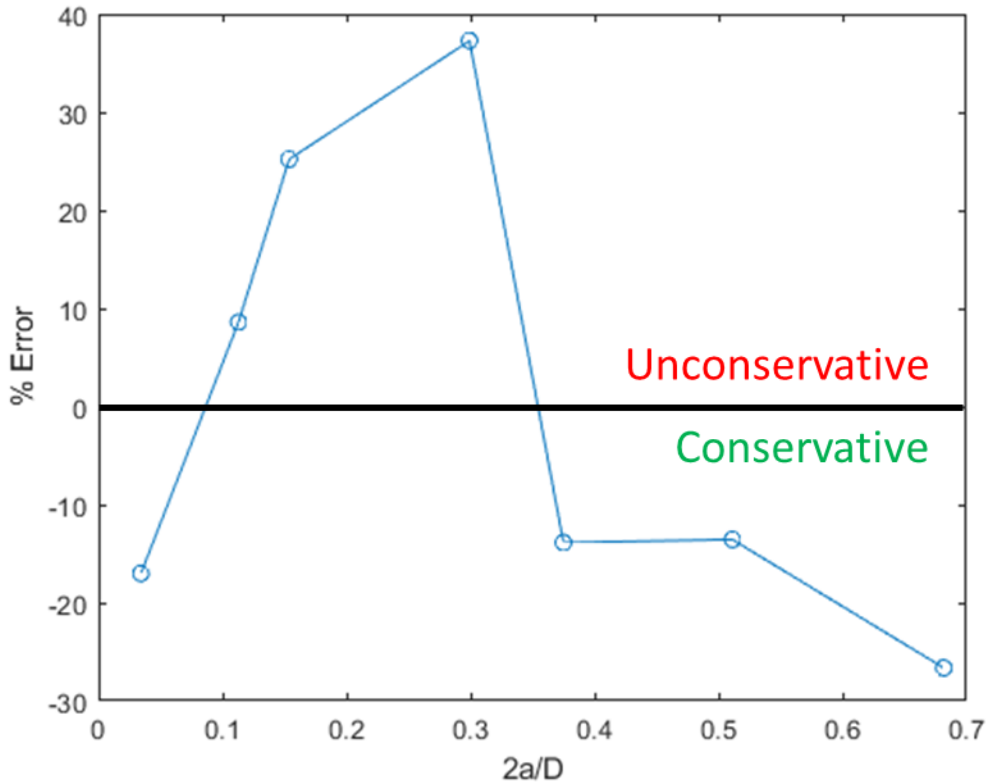


Figure 20 - Percent error modified LEFM model

Shown below is the percent error plotted against crack length. It can be shown that the model is still highly unconservative for crack lengths ranging from 5 to 10 inches in length. Considering that the maximum percent error is almost 40%, using this model would impractical and command utilizing high factors of safety.

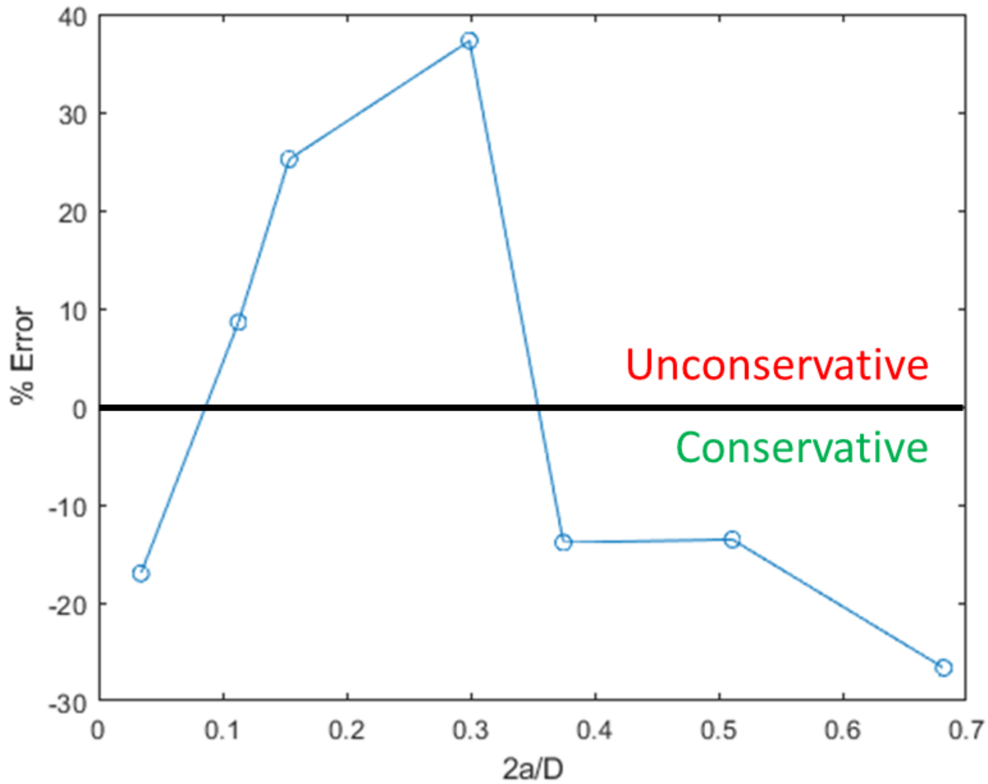
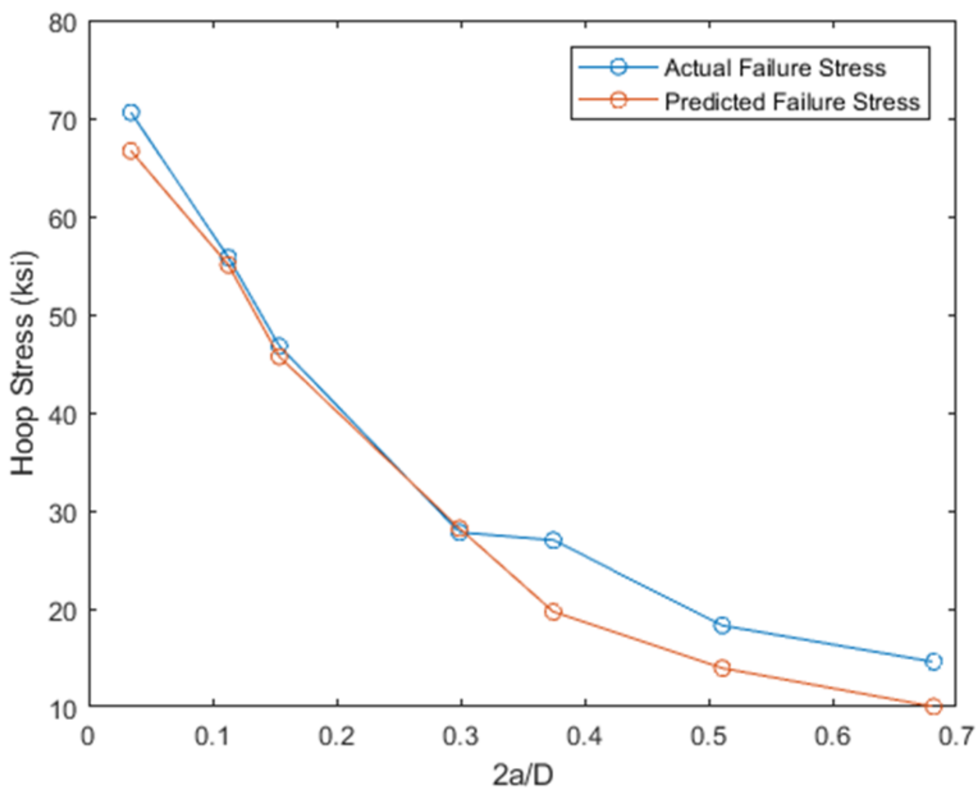


Figure 21 - Percent error of the modified LEFM model

Log-Secant Model

Some of the limitations of the work are that the predicted thicknesses are overly conservative. The Log-Secant model has been shown to be conservative and under predicts burst pressures for low toughness fractures. This means that the composite repairs recommended by the model are slightly thicker than is required. Future work may include the use of the API-579 and PRCI-MAT8 fracture mechanics models to achieve more accurate burst pressure predictions. The modern fracture mechanics models include the effects of residual forming stresses, which can have a significant impact of the results.



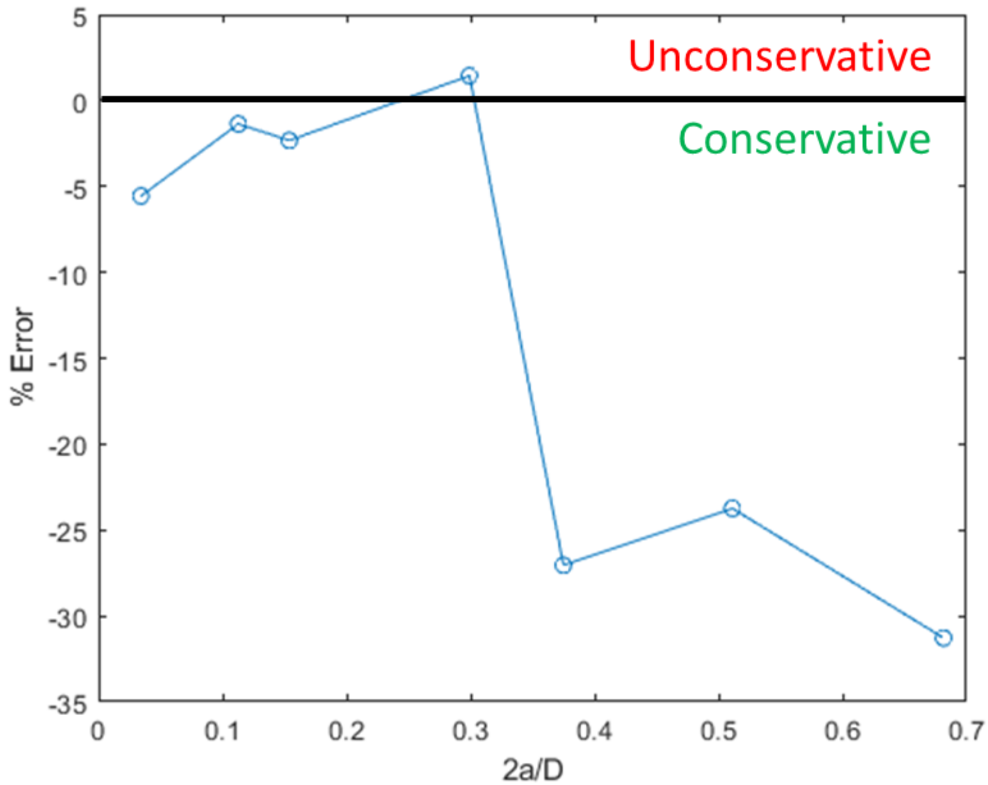


Figure 22 - Percent error Log-Secant model

Modeling Crack Growth of Reinforced Flaws

Modeling fatigue crack growth is out of the scope of this paper. Instead, a minimum design thickness is recommended based on an experimental correlation. However, failure from fatigue is an important consideration in ERW pipelines and should be discussed in future work. Full scale pressure cycling tests have shown that composite repairs can prevent cracks from failing due to fatigue [1]. It is has been shown that reinforcing crack-like defects will prevent fatigue failure up to a certain number of pressure cycles. Future full-scale experiments and theoretical modeling will explore the optimal size to make composite reinforcements in order to limit crack growth.

Here a preliminary approach to modeling crack growth of reinforced flaws is discussed. A good place to start, is to consider a worst case scenario and assume that any crack, no matter how shallow, should be treated as a through wall crack. As a result, the problem is simplified and the burst pressure occurs at a critical crack length.

Modeling through wall flaws

$$\frac{K_c^2\pi}{8c\bar{\sigma}^2} = \ln\left(sec\left(\frac{\pi M_t\sigma_p}{2\bar{\sigma}}\right)\right) \tag{10}$$

Rearranging to solve for predicted hoop stress at failure.

$$\sigma_p = \frac{2\bar{\sigma}}{\pi M_t}\sec^{-1}(e^{\frac{K_c^2\pi}{8c\bar{\sigma}^2}}) \tag{11}$$

$$M_t \cong \sqrt{1 + 1.255\frac{c^2}{Rt} - 0.0135\frac{c^4}{R^2t^2}} \tag{12}$$

$$\bar{\sigma} = Y_s + 10{,}000 \tag{13}$$

$$K_c^2 = \frac{12C_vE}{A_c} \tag{14}$$

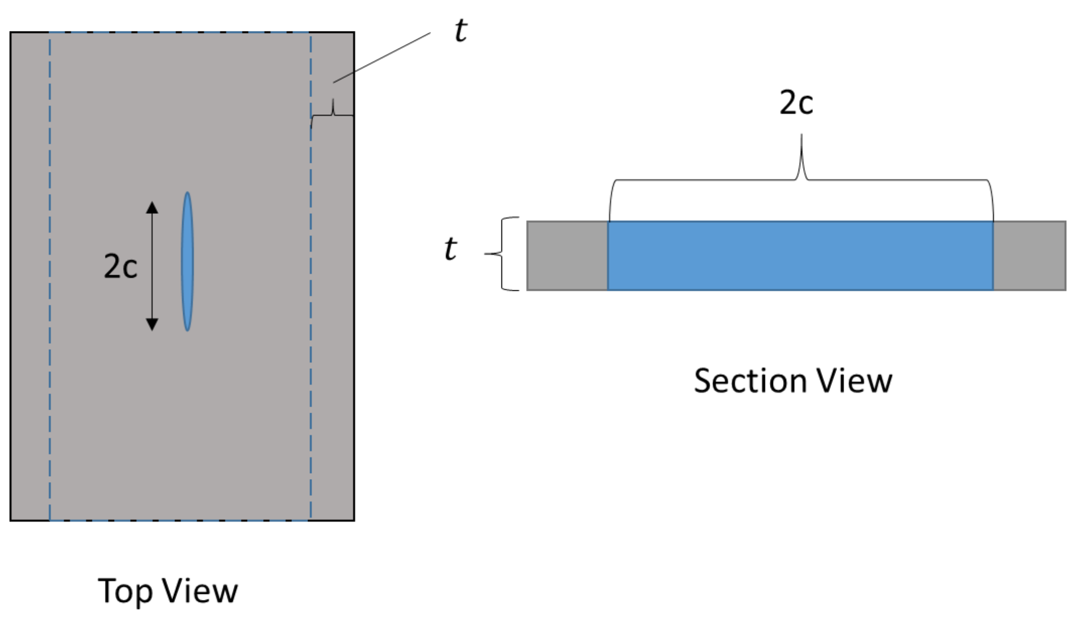


Figure 23 - Modeling through wall cracks using Log-Secant method [5]

Reduced hoop stress in pipe

By introducing a composite reinforcement, it is possible to reduce the hoop stress in a cylindrical pressure vessel such as a pipeline. Shown in Figure 24 is a section view of a reinforced pipeline. The following equation describes how the composite reinforcement shares the load with the steel and lowers the overall hoop stress in the reinforced area.

$$\sigma_{hoop} = \frac{PR}{t_s\left(1 + \frac{E_c t_c}{E_s t_s}\right)} \tag{1}$$

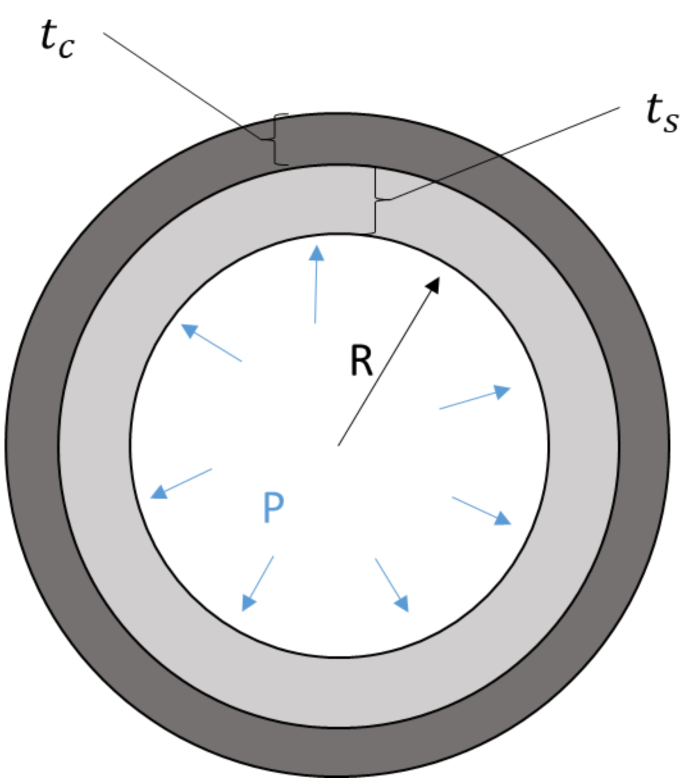


Figure 24 - Section view of reinforced pipeline

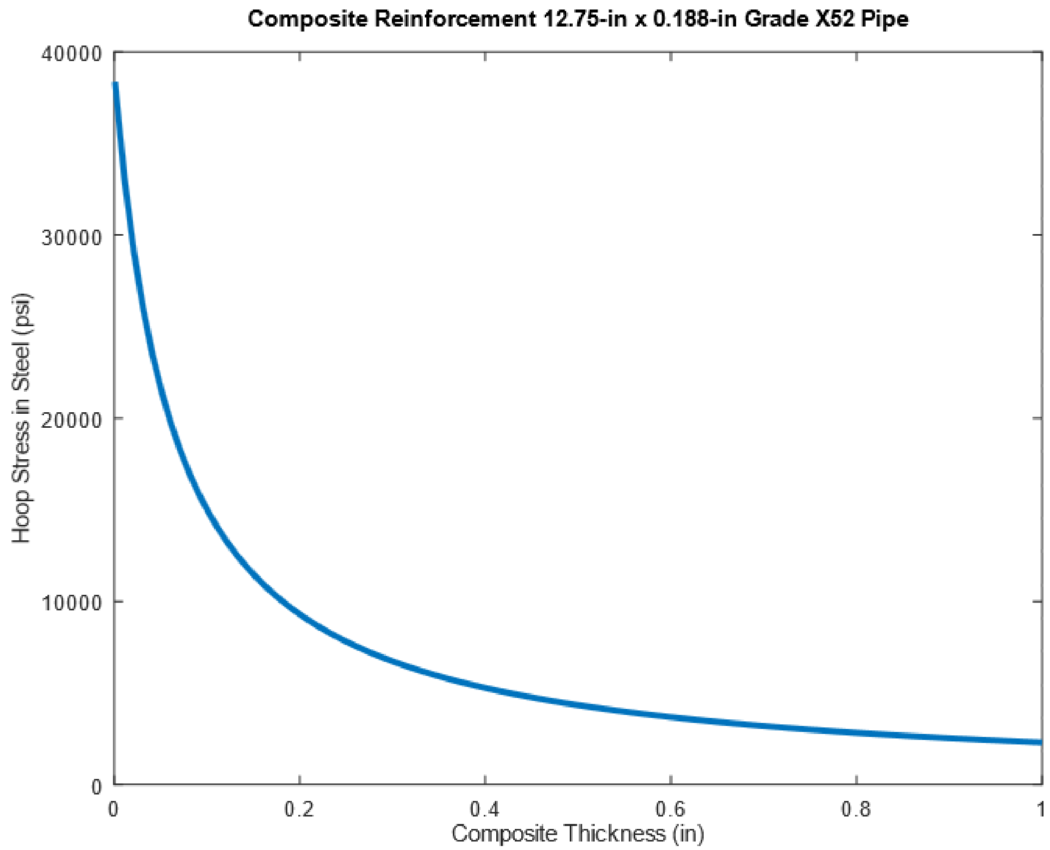


Figure 25 - Plot of hoop stress vs. composite thickness

Paris's law for crack growth

Given a hoop stress in the pipe, it is possible to estimate the critical crack length using numerical root finding techniques such as the bisection or Newton-Raphson methods. Thus, the critical crack length is calculated from the Log-Secant model. However, it may be possible to track the crack growth using LEFM for a through wall crack.

$$\Delta k = \Delta\sigma_{hoop}\sqrt{\pi c} \tag{2}$$

$$\frac{da}{dN} = C\Delta k^{n} \tag{3}$$

$$N = \int_{ai}^{af} \frac{1}{C\Delta k^{n}} da \tag{3}$$

The symbol ai is the initial crack length, and af is the critical crack length calculated using numerical techniques and the log secant method. Where C and n are material properties, N is the number of cycles to failure, and a is the crack length. Note that c is half the crack length see Figure 23. N may be calculated analytically or by using numerical integration. Figure 26 shows the estimated composite thickness required for a flaw to survive a given number of cycles. Note that the 50,000 cycles are equivalent to about 100 years of service.

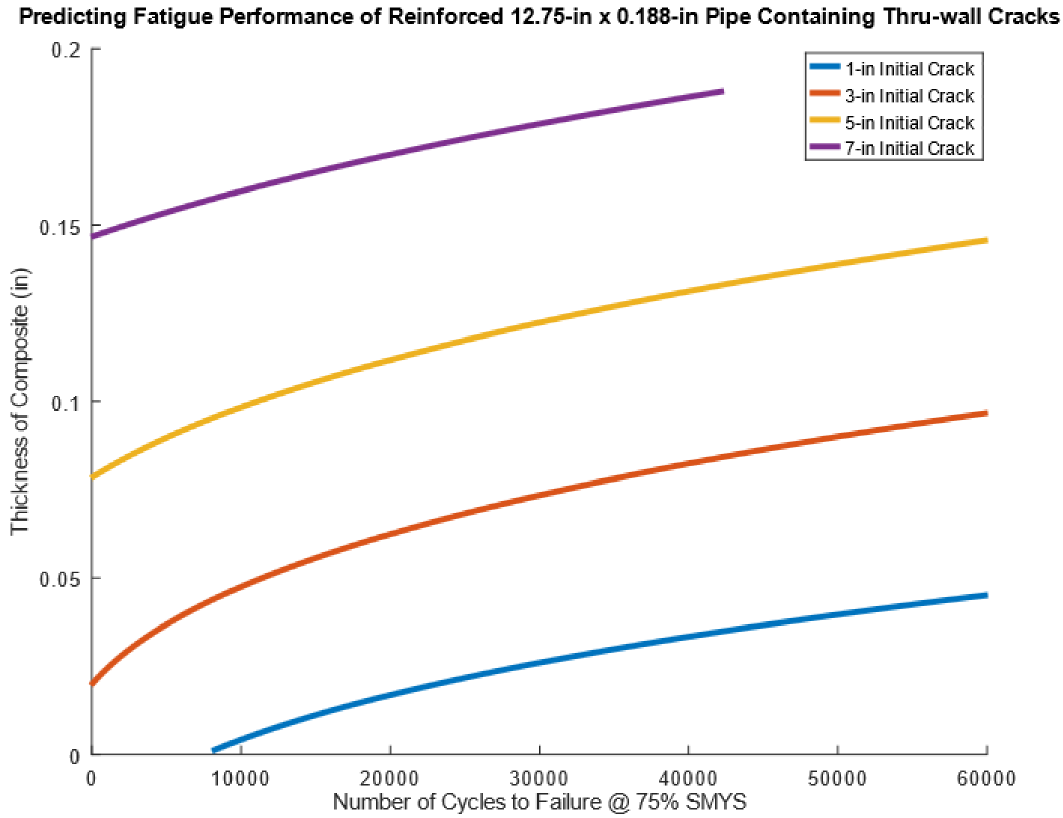


Figure 26 - Estimate for number of cycles to failure based on proposed method

Note that the experimental correlation discussed in Figure 12, would predict a composite thickness of about 0.23-in for 100 years of service life. The proposed crack growth model suggests that a 3-in crack would require only 0.08-in and a 5-in crack would require 0.14-in of composite. While the trends predicted with this model seem correct, the estimated thickness are likely too small. More experimental data is required to make any definitive conclusions.

CHAPTER VI

CONCLUSION

It has been shown that there is a direct relationship between crack length and composite thickness. The thickness of the repairs must increase until the cracks becomes so large that is considered infinite. In such cases, the pipe has been damaged to a point where it can no longer hold any pressure, thus, the composite repair is supporting the entire load. Increasingly deep flaws require more composite reinforcement than shallow flaws. Flaws that occur in relatively tough regions of the pipe require less composite reinforcement than flaws that occur on or near the bondline. Finally, thick walled pressure vessels require more composite reinforcement because their original burst pressure is higher.

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